MULTIPLE PULSE SEGMENTED GAS GENERATOR

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BACKGROUND OF THE INVENTIONS

Field

These relate to gas generators, for example solid propellant gas generators, including those used to supply warm-gas and hot-gas thruster valves. Other examples include inflation devices, including air bags and the like.

Related Art

Solid propellant gas generators are used in rocket, missile, interceptor and other space vehicle flight control systems, among other applications. One or more solid propellant masses, such as grains, rods or other structures, are included in a pressure vessel or other structure having one or more openings. The openings lead to a rocket motor and/or reaction jets that vary the thrust, pitch, yaw, roll or spin rate and other dynamic characteristics of a vehicle in flight. Once a given propellant mass is ignited, combustion or consumption of the fuel typically cannot be stopped, and the entire mass is eventually consumed. Assembly of several discrete masses of solid propellant permits greater flexibility in controlling the vehicle, but each must be constructed separately with its own discrete ignition source or other means for starting combustion and assembled into the vehicle.

Propellant grains are constructed as single-burn grains, layered grains, spiral grains or concentric ring grains. Layered grains and concentric ring grains can be multiple pulse or sequenced ignition grains. Multiple pulse grains extend capability on certain missions, for example for interceptors, by allowing a moderate early thrust, a low-level sustain or mid-range thrust, and a high-end-game thrust. However, some multiple pulse grains may require ignition in a fixed sequence or taking into account a specific geometric configuration, such as require burning from inside out.

SUMMARY OF THE INVENTIONS

Propellant grains, solid propellant gas generators, and similar

structures, including those for use in missiles, gas-generators and thruster valves, can be improved with new configurations and new methods of operation. The apparatus and methods can be used to maintain a substantially constant center of gravity in the generator during operation, and they can provide flexibility in ignition and pressure versus time characteristics developed during operation. While a number of benefits can be provided through these apparatus and methods, one or more significant benefits can still be achieved without adopting every one of the improvements or without following all the steps of the various procedures discussed herein. Additionally, various aspects of the apparatus and methods can be implemented in a number of combinations while still achieving significant benefits.

In one example described herein, a gas propellant grain assembly is provided with at least two pie-shaped grain segments positioned on opposite sides of a line, for example a center line or center axis. The grain segments are spaced apart from each other to provide a channel or passage way axially from end-to-end so that gas produced by consumption of a grain segment can flow in the channel. Where the two pie-shaped grain segments are approximately the same size and substantially symmetrical with respect to each other on each side of the center line, simultaneous ignition of the grain segments helps to maintain a substantially constant center gravity for the assembly, namely the center of gravity remains on the centerline of the propulsion system. In this context, “constant center of gravity” is taken to mean that the center of gravity remains on the centerline of the propulsion system.

Pie-shaped grain segments can be assembled in pairs, and where segments in a pair are ignited simultaneously, constant center of gravity can be more easily maintained. Where the grain segments in one pair are different from those in another pair, for example different in size and/or shape, different in burn rate, or different in gas production, those differences can be used selectively to produce a desired pressure versus time profile for the assembly. The profile can then be used to operate the assembly as desired, for example moderate early thrust, low-level sustained thrust and high end thrust.

Selectivity can also be provided through the configuration and use of igniters or initiators. Grain segments within a pair are typically configured with igniters identically, and the pressure versus time profile through ignition of a given pair can be selected to produce the desired result. For example, each grain segment in a pair can have igniters or initiators on multiple surfaces, and the number of surfaces ignited can be selected based on the desired pressure versus time profile. In several specific examples, each grain in a pair can have igniters on opposite end surfaces, or interior to the grain segment. The pressure produced as a function of time increases when more surfaces or parts of the grain segment are ignited at the same time.

In another example, an assembly includes pairs of grain segments wherein each grain in the pair is substantially similar to the other. Igniter leads extend from an ignition source and are coupled to respective grain segments so that the grain segments can be ignited simultaneously. The grains in each pair are preferably oriented symmetrically with respect to each other, and the igniter configuration for the grains in each pair are preferably identical, or at least symmetrical as well, or they can be ignited in such a way that the burns in opposite grains are symmetrical. The grains in one pair may be configured differently from the grains in another pair, for example in size, shape or other characteristic allowing a different burn result. In one aspect of this example, a passage way extends between fore and aft portions of the grains so gas produced can flow in the passage way. Therefore, if a pair of grains are ignited at both ends, the gas produced at each end can be applied to valves at one end, as desired. Additionally, if a pair of grains are ignited at interior portions thereof, the gas produced thereby can be applied to more than one set of valves.

Ignition sequence and application (whether one, two or more ignition points for each grain) can be controlled by a controller, for example as part of a vehicle guidance and navigation control. The ignition configuration can then be determined in real-time if desired, and modified as circumstances change. More degrees of freedom are provided with more ignition points and with a larger number of discrete grain segments, for example discrete grain pairs. The grain pairs can be all the same size and shape, or different sizes and shapes. For example, two grain pairs configured to produce the same output

as a single pair of grains can be simultaneously ignited to produce the same result as ignition of the single pair of grains, but the controller has the flexibility of igniting the two pairs separately or igniting the two pairs separately or at different ignition points or at different times.

In a further example of a gas producing assembly, first and second grain elements are positioned apart from each other and the first grain element has a first size and shape and the second grain element has a second size and shape substantially similar to the first. A passage way or channel extends between ends of the first and second grain elements. In one example, the passage way is between the grains so that gas produced from the grains can enter the passage way. Preferably, the grains are symmetrical with respect to each other, and may be pie-shaped. The tube or other cylindrical element may extend between the grains and may form the passage way. Additional pairs of grain elements may also be included, preferably where the grain elements in each pair are oriented substantially symmetrically with respect to each other. The additional pairs may include grain elements that are substantially the same in size and shape to the first and second grain elements, or they may be different. Igniter elements can be positioned as desired, for giving the desired flexibility in igniting the grains. Ignition of the grain elements can be controlled by a controller, for selectively igniting the grains to produce a desired effect.

In a further example of a gas producing assembly, a gas producing grain includes first and second surfaces facing in different directions with respect to each other. Igniter elements are applied to the surfaces for igniting the grain, either simultaneously or selectively as desired. The igniter elements can be applied to end surfaces, facing in opposite directions, and/or applied to adjacent surfaces, for example facing approximately perpendicular to each other. Igniter elements can also be applied to interior portions of the grain, for example, to change the characteristics of the burn. The same or similar configurations can also be applied to other grains in the assembly, which may provide greater selectivity in producing a desired effect. For example, where grains are arranged in oppositely arranged pairs, the grains in each pair can have the same igniter configuration, and can be ignited in the same way simultaneously, making it easier to maintain a constant center of

gravity.

In a system for producing gas selectively, for example to produce a desired pressure and time profile, a gas-producing grain element can include first and second ignition elements controlled by a control system for selectively igniting the grain element at one or more parts of the grain element. Where grain elements are arranged in symmetrical pairs and ignited in symmetrical pairs, a constant center of gravity may be more easily maintained. With a number of pairs of grain elements, the control system has greater flexibility in producing the desired burn characteristic. Greater flexibility is also provided through multiple igniter elements applied to discretely different surfaces on a grain or grain pair. Igniting a grain at a larger number of discrete surfaces produces a larger pressure versus time profile. Greater flexibility can be further provided through different-sized grains or grain pairs, allowing the system to select the sequence in which the surfaces on a given grain are ignited and the sequence in which the grain pairs are ignited.

Various steps or methods can be followed to produce the desired effects. For example, where one or more grains are provided with a channel extending between opposite ends of the grain, either or both ends of the grain can be ignited and still have gas available to valves at either or both ends. The channel allows greater flexibility in locating igniter elements on the grains and selecting which locations on the grain are to be ignited. For example, a pair of symmetrical grains can be arranged on each side of a channel with one or more igniter elements on each grain. Where the grains have igniter elements on each end, both ends can be ignited at the same time, if desired. Where the grains have igniter elements on each end and at an interior area of the grain, a controller can decide which igniter elements to trigger.

In another example of a process for producing a gas, a plurality of grains can be arranged so that there is at least a pair of grains symmetrical with respect to each other and the symmetrical grains are ignited or consumed in a manner to keep a constant center gravity for the arrangement. For example, the pair of grains can be ignited so the grains are consumed at the same rate, such as being ignited at the same locations on the respective grains. Where multiple pairs of grains are ignited, they are preferably ignited

so as to maintain a constant center of gravity.

In a further example of a process for producing a gas, at least one gas producing grain is provided within an enclosure and wherein the grain is ignited at discretely different locations substantially simultaneously. In one configuration, opposite ends of the grain can be ignited simultaneously, and where there is fluid communication between the two ends, the gas produced can be applied to valves at either or both ends. In another configuration, the grain can be ignited at an interior location, typically in conjunction with ignition at other points on the grain. Multiple ignition points increase the consumption rate and the pressure versus time profile.

These and other examples are set forth more fully below in conjunction with drawings, a brief description of which follows.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side and partial cross-sectional view and partial schematic of a gas producing canister assembly for use with the present embodiments.

FIG. 2 is a schematic of the end of a grain assembly for use in the gas producing assembly of FIG. 1.

FIG. 3 is a schematic view of a canister assembly similar to that of FIG. 1 showing fore and aft plenums and a grain assembly between.

FIG. 4 is a longitudinal section view of one end portion of the canister assembly of FIG. 1 with a thruster valve assembly.

FIG. 4A is a schematic of an end view of the grain assembly of FIG. 4.

FIG. 4B is an isometric view of a fore end of the grain assembly of FIG. 1.

FIG. 5 is a flow chart showing a possible control scheme for controlling the ignition of the grains in the grain assembly.

FIG. 6 is a graphic illustration of the burn pressure and motor thrust as a function of time for a possible ignition sequence.

FIGS. 7A-E are schematic representations of an example of an ignition configuration and pressure versus time profile for a two pair grain assembly.

FIGS. 8A-E are schematic representations of an example of an ignition configuration and pressure versus time profile for a three pair grain assembly.

FIGS. 9A-E are schematic representations of an example of an ignition

configuration and pressure versus time profile for a four pair grain assembly.

FIGS. 10A-E are schematic representations of another example of an ignition configuration and pressure versus time profile for a four pair grain assembly.

FIGS. 11A-E are schematic representations of another example of an ignition configuration and pressure versus time profile for a two pair grain assembly.

FIGS. 12A-F are schematic representations of another example of an ignition configuration and pressure versus time profile for a two pair grain assembly.

DETAILED DESCRIPTION

The following specification taken in conjunction with the drawings sets forth the preferred embodiments of the present inventions in such a manner that any person skilled in the art can make and use the inventions. The embodiments of the inventions disclosed herein are the best modes contemplated by the inventor for carrying out the inventions in a commercial environment, although it should be understood that various modifications can be accomplished within the parameters of the present inventions.

Gas producers take a number of configurations and have a number of applications. One application is providing propellant for rockets, missiles and other flight and space vehicles, and the examples given herein will be directed to those types of applications. However, it should be understood that the examples described herein apply to a number of apparatus and configurations used for producing gas, whether as a propellant, for inflation, or otherwise. Therefore, the discussion herein is not limited to any particular application. Additionally, the examples given herein are a small number of applications to which these inventions can be applied, and it should be understood that other examples and other applications can be made without departing from the inventions.

More than one invention is discussed herein and each has benefits that can be derived from using the inventions. However, it should be understood that not all aspects of each invention need to be used to take advantage of

one or more of the benefits provided by these inventions. Some applications may achieve a significant benefit without adopting all of the aspects and features described herein.

In one example of a housing for a gas producing assembly 100 (FIGS. 1-3), a pressure vessel in the form of a canister 102 typically includes a cylindrical wall 104 sized in diameter to suitably fit within an appropriate vehicle. The cylindrical wall 104 includes a fore end wall 106 converging to a forward polar boss 108. The use of the terms "fore" and "aft" with respect to the assembly are used solely as a point of reference for the structures depicted in the drawings, and are not limiting as to particular types of structures to which those terms are applied. However, in the context of a vehicle in which these assemblies may be used, these terms are used as an indication of their anticipated orientation once in place in the vehicle. In the context of other applications, other terms may be used to refer to the same parts of the assembly without connoting direction or orientation. As depicted in FIG. 1, the fore end wall 106 is substantially the same as the opposite wall on the right side of the drawing, and the two ends can be interchangeable in the example shown in FIG. 1 until the assembly 100 is configured to be mounted to output valves, for example. For purposes of the present discussion, it will be assumed hereafter that the polar boss 108 is to be coupled to a valve assembly 108a, for example divert thrusters of a vehicle and their respective nozzles (shown schematically in FIG. 4).

The valve assembly is fed by a manifold attached to an exit duct, in the form of the polar boss 108. O-rings 108b and 108c or other seals prevent leakage in the area of the polar boss and the corresponding manifold.

The cylindrical wall 104 includes an aft end wall 110 converging to an aft polar boss 112 (FIG. 1). The aft polar boss 112 is connected through a manifold (not shown) to an attitude control system and corresponding attitude control valves, as is known to those skilled in the art. Corresponding O-rings or other seals are included to prevent leakage between the aft polar boss 112 and its manifold and the attitude control system. In an alternative configuration, the aft polar boss 112 can be omitted in favor of a single output. The canister is a carbon fiber reinforced resin shell wrapped about the grain assembly, described below.

An insulating layer 114 extends from the fore polar boss 108 to the aft polar boss 112. Each end of the insulating layer is integrated with the respective polar boss structure, and the insulating layer intermediate the ends has the same contour as the canister wall around it.

A gas propellant assembly may include one or more discrete propellant segments or elements, shown in one example in FIG. 2 as substantially pie-shaped elements including a first grain 116, a second grain 118, a third grain 120, a fourth grain 122, a fifth grain 124 and a sixth grain 126 in the illustration. The grains are substantially pie-shaped except for a center opening area 128 extending longitudinally the length of the grains and concentric with a center axis 130 (FIGS. 1-2). Each grain can take a number of sizes, shapes, orientations and configurations, but in the examples described, each grain is shown as having a pie-shape and each grain is shown as having the same length as all of the other grains. While all of the grains can be formed to have the same size, the example of the grain assembly 132 shown in FIG. 2 has grains of two different sizes for purposes of illustration. The grains can also be formed to be all different sizes or to have some of the grains the same size and other grains different sizes. Additionally, grains can be formed with various and different propellant formulations. Formulations can provide low pressure slow burns, high pressure fast burns or burns in between, as desired. However, a preferred example has the grains in a given pair being consumed in such a way as to help to maintain a constant center of gravity.

There are also other factors that may be considered in determining grain configuration, as may be seen by considering common equations used in gas generators. As reflected in those equations, the pressure can be considered by equating the generated mass flow rate (Eq. 1) and the exhaust mass flow rate (Eq. 2), as follows:

$$\text{Mdot} = (P/P_0)^n * r_{b0} * As * \rho_s \qquad \text{(Eq. 1)}$$

where

P = pressure
P_0 = reference pressure (typically, 1000 psia)

r_{b0} = reference burnrate at P=P0
As = burning surface area
n = pressure exponent
ρ_s = propellant solid density

and

Mdot = P * Ae * K / $\sqrt{T}$ (Eq. 2)

where

Ae = exit (exhaust) area
K = gas flow constant
T = gas burn temperature.

By equating both flowrates, the steady pressure P is:

$P = ((r_{b0} * As * \rho_s * \sqrt{T}) / (Ae * K))^{(1/(1-n))}$ (Eq. 3).

Therefore, among others, additional factors that may be considered when selecting a grain configuration include the burn rate, burning surface area, and the exhaust gas exit area. These factors may be used by a design team to select the grain configuration to suit the desired function or result.

A gas propellant grain assembly may be formed by at least one grain element 133 having a first side portion in the form of a fore end 134 (FIG. 2A) and a second side 136 facing in different directions from each other. The second side 136, in the form of the grain shown in FIG. 2A, is one side of the pie-shaped grain or wedge shape, and the grain may include another wedge side 138 also facing a different direction than the fore end 134. The grain element 133 has an inner portion or side 140 also facing in a direction different from the fore end 134, and an outer surface 142, also facing in a direction different from the fore end 134. The grain element 133 includes an aft end 144 likewise facing a direction different from fore end 134.

The gas propellant grain assembly shown in FIG. 2A also includes a first igniter element or initiator 146 adjacent and preferably in secure contact with the fore end 134 and a second igniter element 148 adjacent and preferably in secure contact with the aft end 144. The igniter elements can be used to selectively ignite the grain at one or both surfaces of the grain. The selection of which surface to ignite and whether to ignite both surfaces

simultaneously or sequentially can be made under the control of a suitable processor or controller. In the configuration shown in FIG. 2A, the igniter elements are placed on oppositely facing surfaces of the grain. However, the igniter element 148 can also be placed on one or more of the other surfaces, as desired. It should be noted, however, that use of an igniter element on the outer surface 142 is generally not desirable where the outer surface 142 would be bonded, adhered to or otherwise fixed to the insulating layer 114, which in turn is fixed relative to the canister 104. Igniting the outer surface 142 may lead to loosening of the grain element 133 relative to the pressure vessel in which it is contained. Additionally, igniting of opposite surfaces tends toward symmetrical consumption of the grain relative to a midpoint between the two opposite surfaces.

Instead of or in addition to one of the igniter elements 146 and 148, an igniter element 150 may extend into an interior portion of the grain 133. "Interior" in the present context refers to a location between surfaces, for example a location between the end surfaces. Where the igniter element 150 is interior to all of the surfaces 134, 136, 138, 140, 142 and 144, the igniter element 150 would most likely enter through an opening, for example a slot, in the grain structure, formed for example when the grain is formed. The slot preferably includes an opening facing the curved surface 140. In this context of an igniter lead on an interior portion of the grain, the grain is still considered a grain element or grain segment when the portions of the grain on each side of the slot and igniter element 150 are connected to each other by burnable grain material. By applying an ignition pulse to the interior igniter element 150, combustion of the grain can proceed more quickly, producing a larger propulsion magnitude as a function of time. Placement of the interior igniter element 150 is preferably made so as to encourage relatively symmetrical consumption of the grain while minimizing the possibility of separation of the grain from the insulating layer or from the canister 104.

The grain assembly can also include a control system or controller 152 (FIG. 2A) for controlling each of the igniter elements. The controller would be positioned within the vehicle as desired, in accordance with conventional practices. The controller is programmed to send ignition pulses to one or more of the igniter elements in accordance with a predetermined sequence or

schedule. Alternatively or additionally, the controller may be programmed to acquire data on a real-time basis and ignite one or more of the igniter elements according to criteria stored in the control system or communicated to it externally. The extent to which the ignition mode is predetermined or determined in real-time may depend on the mission, purpose or assignment for the vehicle.

The grain 133 is preferably a solid propellant grain. It is cast into an insulated and inhibited mold in accordance with procedures known to those skilled in the art. Igniters are embedded between the grain and respective peel-away inhibiting covers at the desired locations. The inhibiting layer at other locations are bonded to the respective grain segment. The shape of the grain can be formed so as to provide a passage way between the fore and aft ends 134 and 144, respectively, so that propellant gas may flow in the passage way. In the grain 133 shown in FIG. 2A, the inner surface 140 may be formed concave to form the passage way. Other forms may be used to form the passage way. Formation of the passage way may depend on the shape of the grain in combination with the shape of the pressure vessel the grain is placed in. Alternatively, the passage way may be formed through the shape of the grain (or several grains where more than one grain is used) without regard to the shape of the pressure vessel.

While a gas producing assembly may be formed from a single grain, such as that having the characteristics described with respect to the grain 133 of FIG. 2A, assemblies having more than one grain are used also. An assembly having two grains will be described for purposes of illustration in the context of FIG. 2, formed from the first grain 116 and the second grain 118. Each of the grains will be considered to have one or more of the characteristics described previously with respect to the grain 133, the characteristics to be selected as desired. Additionally, the characteristics selected with respect to the first grain 116 are preferably the same as, though need not be, the characteristics selected with respect to the second grain 118. The characteristics of the two grains may be selected to be identical, for example to help in maintaining a constant center gravity if the grains are ignited simultaneously and at complementary locations. However, it should

be understood that the grains can be configured otherwise if constant center gravity is not a significant concern.

A gas producing assembly may include a first grain 116 and a second grain 118 having surfaces such as inner surfaces 154 and 156, respectively, spaced apart from each other. In the example shown in FIG. 2, the first and second grains and their inner surfaces are spaced apart from each other on opposite sides of the center line 130 and form part of the opening 128 forming a passage way extending axially concentric with the center line 130. The first and second grains are shown in FIG. 2 as being separated from each other by the third, fourth, fifth and sixth grains, but in the present example the first and second grains are considered as substantially semi circular grain portions bonded together to form a two-piece pie-segmented cylinder with a passage way extending between them centered on the center line 130 between the fore and aft ends. In this configuration, the first and second grains 116 and 118, respectively, are substantially similar in cross-section and are preferably substantially similar in length. In this form, the first and second grains are substantially symmetrical with respect to each other, and they are shaped and positioned so as to be substantial mirror images of each other with respect to a plane separating the two. Each of the grains also preferably has the same number and configurations of igniter elements so that the grain assembly is formed from a pair of substantially identical pie-shaped grain elements that are symmetrical with respect to each other. The first and second grains each include respective bonded layers and peel-away inhibitor layers, as necessary (as do all of the grain elements described herein), and they are covered with an insulating layer, with their outside surfaces bonded to the insulating layer so as to support the grains within the pressure vessel. Upon ignition, the propellant gas may enter the passage way 128 and be applied to valve assemblies as desired.

In the configuration of the gas producing assembly just described with first and second grains 116 and 118, respectively, the grain assembly is formed from two substantially similar grains. Upon ignition, they are preferably consumed as a pair, preferably maintaining a constant center of gravity, for example by applying ignition pulses at identical locations on the

grains in the pair. A suitable controller selects which of the surfaces or grain portions are ignited.

In another configuration of a gas producing assembly, the assembly may include the first pair and a second pair of grain elements formed from the third and fourth grains 120 and 122, respectively. In this configuration, each grain is selected to include one or more of the characteristics of the individual grain 133 described above with respect to FIG. 2A. Each grain is also preferably formed in the same way. The third and fourth grains 120 and 122 have surfaces, such as inner surfaces 158 and 116 spaced apart from each other on each side of the center line 130 so they form part of the passage way defined by the opening 128. The grains in the first and second pairs are bonded together to form a pie-segmented cylinder with grains in each pair oriented opposite each other relative to the center line 130, and with the grains in each pair preferably substantially similar to each other. While the grains in the second pair may have a length different from each other and from the length of the grains in the first pair, the example of this configuration of a gas producing assembly has the lengths of the grains in both pairs identical to each other. While the grains in the second pair can be the same size as the grains in the first pair (see, for example, the configurations shown in FIGS. 7A-7E and 11A-11E), the third and fourth grains 120 and 122, respectively, are preferably a different size, for example having a shorter arc length, compared to the grains in the first pair (see, for example, the configurations shown in FIGS. 12A-12F). Having grain pairs of different sizes allow a controller to selectively ignite grain pairs to produce a desired pressure versus time profile. Likewise, the ignited surfaces on the grains within a given grain pair may also be used to determine the output profile for the grain assembly. The grains in the first and second pairs are covered with an insulating layer, with their outside surfaces bonded to the insulating layer so as to support the grains within the pressure vessel. Upon ignition, the grains in each pair are preferably consumed together, at the same rate, as determined by the application of the ignition pulses by a controller (as well as the makeup of the grain), while ignition of one pair does not cause ignition of the other pair.

Grain segments within a pair, or grains from one pair to the next may

be formed from different materials or molded in ways different from each other so as to produce a different pressure versus time profile. Consequently, a controller can select the grain segments or the grain pairs based on their makeup to provide the desired output. However, it will be assumed for present purposes of illustration that the grain segments in each pair, and the pairs of grain segments from one pair to the next have the same chemical composition or propellant formulation.

In a further configuration of a gas producing assembly, the assembly may include the first and second pairs of grain segments formed from the first, second, third and fourth grains 116, 118, 120 and 122, respectively, as well as a third pair of grain segments comprised of grain segments 124 and 126 (FIG. 2). In this configuration, like those described before, each grain is selected to include one or more of the characteristics of the individual grain 133 described with respect to FIG. 2A. The grains are also preferably formed in the same way. The fifth and sixth grains are preferably symmetrical with respect to each other about the center line 130, and include inner surfaces 162 and 164 spaced apart from each other on each side of the center line 130 to form part of the passage way defined by the opening 128 along with the inner surfaces of the other grain segments. The grains in the third pair of grains as shown in FIG. 2 have substantially the same shape as the second pair of grains, and in this example, have substantially the same length as the other grains in the assembly. However, the third pair grains may have a different size, length, shape or other characteristics so that consumption of the grain produces a different result compared to consumption of the other grains. The grains in the first, second and third pairs are bonded together to form a pie-segmented cylinder with grains in each pair oriented opposite each other relative to the center line 130. As before, having grain pairs of different sizes allow a controller to selectively ignite grain pairs to produce a desired pressure versus time profile. Similarly, selecting surfaces on the grain pairs to be ignited may also be used to determine the output profile for the grain assembly.

The grains of the first, second and third pairs are covered with an insulating layer, with their outside surfaces bonded to the insulating layer so as to support to grains within the pressure vessel. Upon ignition, the grains in a given pair are preferably consumed together, at the same rate, as

determined by the application of the ignition pulses.

A given grain assembly may be formed about a tube 166 (FIG. 3) extending along the passage way formed by the inner surfaces of the grain segments. The tube 166 forms a channel along with the polar bosses 108 and 112, so that gas produced from any portion of the grain segments can be applied to the valve assemblies at either end through either the fore plenum 168 or the aft plenum 170. Where a single polar boss is used, for example only fore end polar boss 108, gas generated through ignition at or near the aft end reaches the polar boss 108 through the tube 166, for example through openings therein. The tube may be formed from a high temperature phenolic, and may include reinforcement such as carbon fiber reinforcement. The tube forms part of each polar boss, provides a gas flow path between fore and aft burning surfaces and it carries igniter leads embedded in its wall, as shown in FIG. 4.

If desired, the tube 166 supports the grains interiorly. In one example, the interior surfaces of each grain (once they are covered with their respective inhibitor layers), such as inner surfaces 154, 156, 158, 160, 162 and 164 (FIG. 2) are bonded to the respective adjacent surface portions of the tube 166. The bonding is done in substantially the same way that the perimeter surfaces of the grain inhibitor covers are bonded to the outer insulation of the pressure vessel.

Solid propellant grains are cast into insulated and inhibited molds, and the segments are then bonded together to form a pie-segmented cylinder. Bonding and inhibiting material 171 extends between each of the pie segments, between each pie segment and the tube 166 and around the perimeter surface of each pie segment. One or more igniter leads 172 extend from a respective igniter 174 embedded between the grain and its inhibiting cover 174A at the fore end, as shown in FIG. 4, and/or at the aft end (not shown). The igniter leads 172 extend from the grain substantially radially inward to the tube 166 and inboard of the respective polar boss 108. The igniter leads are embedded in the tube and exit through a wire pass-through 175. The leads then extend axially forward to be coupled to a suitable control system, for example control system 152 described with respect to FIG. 2A.

If igniter leads are embedded in the aft end surfaces, they may be embedded in the tube and exit out the aft polar boss and extend to the control system. If there is no aft polar boss or exit, the aft igniter leads may extend through the tube to the forward end. Igniter leads could also be routed to the grains to allow mid-section burning, and suitable openings would be formed in the tube 166 to allow the gas to enter the tube. Igniter leads can also be routed along the canister wall, inside the carbon fiber envelope (referenced below) and outside the insulation layer (also referenced below). Such case wiring with the outer disposed igniter leads can exit through their own separate electrical connector boss adjacent or around the polar boss or in the area of the plenum.

In the example of the assembly shown in FIG. 4, the igniter leads 172 are imbedded in the tube 166 during fabrication or forming of the tube 166 so as to exit the tube radially. In the preferred form, each igniter 174 on a given grain includes its own igniter lead 172 separately and individually controllable through the controller 152. As depicted in FIG. 4B, where part of the fore end of the tube 166 is removed, each of the individual igniter leads is shown. Leads 172A and 172B are coupled to grain 120 and leads 172C and 172D are coupled to grain 124, etc. Each of the igniter leads are preferably coupled to respective switches or an appropriate switch or control array in the controller in such a way that the leads can be independently and separately energized or triggered as determined by the controller. With such a configuration, each igniter in the assembly can be controlled separately and ignited separately, both in terms of whether or not the igniter will be energized and the timing of any such ignition. Therefore, each of the igniters 172A-172L is preferably separately controllable by the controller, allowing the controller to separately control any ignition of any igniter on any point on a grain, as well as the timing of any such ignition.

Openings 176 (FIG. 4) extend radially through the side walls of the tube and/or polar boss 108 at the fore end of the tube to allow gas flow from the grain surface into the center of the tube and out any exit to which the tube is connected. Preferably the openings are uniformly distributed about the tube and are sized to allow unrestricted gas flow.

The grain assembly or bonded cylinder is then covered with an insulating layer 178 and then encased within the generator case 180. The generator case 180 is a wrap of carbon fiber and resin bonded to the insulating layer 178 and to the tube and polar boss combination outboard of the openings 176 to the forward end 182 of the polar boss 108. The generator case 180 is also bonded to the aft tube portion and polar boss. Thruster valve assemblies are attached to the tube and polar bosses outboard of the lead exits. O-rings or other seals around the polar bosses guard against pressure leakage. The valve assemblies can be tied together about the canister or to lugs formed on the canister to help stabilize the valve assemblies against the thrust developed in the gas generator. Each gas exit may include a sonic choke feature to guard against the effects of manifold back-pressure.

Assemblies incorporating the concepts represented by the foregoing examples provide greater flexibility and options for vehicles and other systems in which these assemblies can be used. They can provide greater flexibility and selectability in ignition sequences and/or ignition locations and in propulsion profiles, as illustrated below. Advantages are available by relying on symmetry in grain geometries, igniter locations, the igniters fired, the sequences of ignition as well as other grain characteristics/configurations. Grain assemblies can be more reliably supported, and ignition profiles can be tailored to maintain a relatively constant center of gravity in the assembly.

A controller or other means for determining the timing and sequencing and location of grain ignition, such as controller 152, can be used to give the desired level of flexibility and control over operation of the gas producing assembly. Hardware and algorithms or firmware can be incorporated into the controller as desired to give the desired level of control.

As an example of steps that can be followed in a controller for operating a gas producer such as those discussed herein, possible steps are depicted in FIG. 5. Once the assembly is initiated, started or armed, either separately or as part of an overall system of which the gas producer is a part, the controller may undergo a system check 184, including incoming data connections, sensor testing, and the like. Once all systems are operational, the controller will continue checking for incoming data or instructions, and

upon receipt of an ignition signal 186, the controller can evaluate using the algorithms and data available to it and select a grain pair and ignition point configuration 188 for producing the desired gas production and pressure versus time profile. In the case of a launch of a vehicle, the ignition sequence may be predetermined to make the requirements of separating the vehicle from the launch system, protecting surrounding structures, minimizing detectable gas trails, or the like. In other situations, the ignition sequence may be determined as a function of incoming data from sensors, master controllers or other sources.

Based on control signals from the controller, the first grain pair is ignited 190, through hot gas pressure from an igniter, and ignition of the grain segment causes the inhibiting cover to split and peel back, allowing gas to escape from the grain pair. For example, a medium-sized grain pair can be ignited to start a mission, producing a medium gas pressure with productive divert maneuvering in the early stages of the deployment. As shown in FIG. 6, ignition of a first grain pair can produce a first thrust profile 192 having a relatively uniform pressure that may last an extended period, for example approximately 20 seconds. Other initial ignition schemes are also possible. While the discussion focuses on igniting grain pairs as examples, it should be understood that grains can be ignited in a number of configurations and combinations. In the present examples, grains are ignited in symmetric pairs to help in maintaining a constant center of gravity for the gas producing assembly.

With successful ignition of the first grain pair, the controller evaluates the target configuration and time of flight 194 (FIG. 5), for example by receiving information about the target speed, acceleration, direction or vector, and by evaluating the elapsed time from the first ignition. On this basis, the controller can select the next grain pair and their ignition points to achieve the desired propulsion or pressure versus time curve for the next stage. Information about the available grain pairs, their ignition configurations and their gas producing characteristics can be maintained in a database, lookup table or other suitable information area for use by the controller. The configuration of this information may be determined as a function of the vehicle type, missions for which the vehicle is designed, and the like.

Based on the outcome reached by the controller, a second grain pair is ignited 196, for example to produce a sustained thrust 198 (FIG. 6), for example for another 20 seconds. Upon successful ignition, the controller may continue to evaluate the target configuration, the estimated time to intercept and the elapsed time of flight 200. Based on that evaluation, the controller continues selecting grain pairs and ignition points for ignition in the next phases of the vehicle operation. For example, the controller may produce signals to the selected set of igniter leads to ignite the next to last (N-1) grain pair for producing a pulse 204 (FIG. 6) for high thrust and pressure. These grains may have the greatest surface area and may be ignited from the largest number of ignition points possible to produce maximum pressure and thrust, even though for a shorter elapsed time. The process of evaluation and grain selection continues 206 (FIG. 5), if and as necessary, and grain pairs are ignited until the last grain pair (Nth pair) is ignited 208.

Examples of steps 188-196 are depicted in FIGS. 7A-E, 11A-E and 12A-F, showing ignition of two pairs of grains, where N = 2. The ignition configurations for the examples shown in FIGS. 7 and 11 are different while the grain sizes are substantially the same, and the ignition configuration and the grain sizes in FIG. 12 are different from the other examples. Examples of steps 188-202 are depicted in FIGS. 8A-E showing ignition of three pairs of grains with a given ignition configuration and where the second and third grain pairs are the same size but different in size from the first grain pair. In this example, N = 3. Examples of steps 188-208 are depicted in FIGS. 9-10, showing ignition of four pairs of grains, where N = 4. The first pair of grains is larger than the other pairs of grains taken separately, and the other pairs of grains may be different in size or similar in size. All of the grains in FIG. 10 are the same size as each other. The ignition configuration in FIG. 9 is different than the ignition configuration in FIG. 10. It will be assumed for purposes of these examples that all of the grains are substantially the same length, as represented by the grain lengths in FIGS. 7B-12B, and have substantially the same chemical composition, though other configurations of grain segments can be used by changing the length and/or the chemical composition either with or without others of the changes described herein. It is also noted that both grains in a given pair are ignited simultaneously at

identical ignition locations with identical ignition configurations. While other ignition configurations are possible, non-symmetrical consumption of grain pairs may make difficult maintaining a constant center gravity for the assembly. The grain pairs of the examples of FIGS. 8-12 are also combined in such a way as to provide a passage way or channel between them. The channel provides an opening for gas to travel between the ends of the grain pairs. Such a channel is useful if there is a single output for the gas producer and both end surfaces of a grain are ignited, or where gas produced at multiple locations of a grain are to be made available at more than one output. However, other means may be provided for allowing gas flow, if desired.

The grain and ignition configurations 210, 212 and 214 of the example of FIG. 7 are depicted in FIGS. 7A, 7C and 7D, which show that only the fore end surfaces are ignited, they are ignited in sets of oppositely-facing or symmetrical pairs and that they are ignited in sequence as opposed to simultaneously. The lower case "f" in FIG. 7A indicates that the fore end surfaces are ignited for both pairs. FIG. 7C depicts a representation that none of the aft end surfaces are ignited. FIG. 7D illustrates the sequence of ignition of the pairs of grains as well as the ignition surfaces. Additionally, the second pair of grains is ignited before the first pair of grains are consumed, as indicated in the pressure versus time chart 216 depicted in FIG. 7E. It will be assumed for purposes of this example that the grain compositions in each grain segment are identical, that their lengths are substantially the same as indicated in 218 of FIG. 7B, that their ignition lead configurations are substantially the same, and that the other aspects of the grain segments and their configurations are otherwise substantially the same.

FIG. 7E is a schematic depiction of a pressure versus time chart along the lines of the burn pressure and motor thrust chart of FIG. 6. FIG. 7E depicts a moderate level of pressure for a sustained length of time. The numeral "1" represents the thrust attributable to simultaneous ignition of the first pair of grains. Before the complete consumption of the first pair of grains, the controller ignites the second pair of grains, the pressure for which combines with the pressure produced from the gases resulting from the combustion of the first pair of grains to provide a burst of pressure for a given length of time, as indicated by the width of the peak numbered "2".

The grain and ignition configurations 220, 222, and 224 of the example of FIG. 8 are depicted in FIGS. 8A, 8C and 8D. These schematics show that the fore end surfaces 1-3 of the grain pairs are ignited, and that the aft end surfaces of the third pair ("3a") of grains are ignited. Additionally, the example depicted in FIG. 8, like the other examples, show the grain segments are ignited in symmetric pairs. FIGS. 8D and 8E show that the grain pairs are ignited with a discrete delay between each ignition, and not simultaneously. While the configuration of the ignition leads can be different for the three pairs of grain segments, having a full complement of ignition leads provides the most flexibility in igniting the grain pairs. For example, even though the aft end surfaces of two of the pairs are not ignited, igniter leads on the aft end surfaces may be preferable to provide the controller with greater flexibility in the ignition capabilities.

The pressure versus time chart 226 FIG. 8E depicts a relatively high level pressure for a moderate length of time developed through ignition of the first grain pair. As the first grain pair approaches complete consumption, the controller ignites the fore end surfaces of the second pair of grain segments, which are smaller in size than the first pair. The second pair produces a sustained level of pressure for a similar length of time, near the end of which the controller ignites the fore and aft end surfaces of the third grain pair. Even though the second and third pairs of grains are substantially the same size, ignition of both ends of the third pair of grains results in greater gas production over a shorter period of time, thereby producing a high-pressure pulse. From these FIGS. 8, the effects of grain size and ignition configuration can be seen in the resulting pressure versus time profile.

The grain and ignition configurations 230, 232, and 234 of the example of FIG. 9 are depicted in FIGS. 9A, 9C and 9D. Only the fore end surfaces of the first grain pair, the largest of the four grain pairs, are ignited, while both the fore and aft end surfaces of the second, third and fourth grain pairs are ignited. The grain pairs are ignited in a discrete sequence rather than any two pairs being ignited simultaneously, and each of the second, third and fourth pairs are ignited in their order before the first pair of grains is consumed. While aft end leads for the first grain pair are not required in this ignition sequence and configuration, and interior ignition leads are not used on any of

the grains, including such leads provides greater flexibility for the controller and the ignition configuration.

The pressure versus time chart 236 of FIG. 9E shows the gas production from the first pair of grains has a moderate level and a relatively sustained period of time, and the ignition of the second pair of grains follows shortly after the ignition of the first pair. The second pair is consumed well before ignition of the third pair, so that gas produced from the second pair does not contribute to thrust developed upon ignition of the third pair. Likewise, ignition of the fourth pair receives no contribution from gas produced through ignition of the third pair. However, pressure produced from ignition of the first pair contributes to the pressure and thrust developed through ignition of each of the other pairs of grain segments.

FIGS. 10A, 10C and 10D show the grain and ignition configurations 240, 242, and 244 of the example of FIG. 10, showing that only the fore end surface portions of the first and third grains are ignited, while both the fore and aft end surfaces are ignited in the second and fourth pairs of grains. Here all of the grains are approximately the same size and preferably have the same ignition lead configuration, for flexibility for the controller. The second pair of grains is ignited before complete consumption of the first pair of grains, and ignition of both ends of the second pair of grains results in faster consumption of the second pair. In this example, a level of sustained pressure and a peak pressure are provided with essentially identical pairs of grains by using different ignition configurations. The first pair burns longer because only one end surface of the grains was ignited, while the grains in the second pair are consumed more quickly with a higher pressure result when both ends are ignited simultaneously. Similar comments apply to the geometric and ignition configurations of the third and fourth grain pairs. It should also be noted that the overall pressure versus time profile 246 of the example of FIG. 10 is similar to the pressure versus time profile created by the ignition configuration created through the first, second and third pairs of grains in FIG. 9. Therefore, similar results can be obtained even though grain segments in the two examples may not be the same, and the ignition configurations may not be the same.

The grain configurations 250, 252, and 254 of the example of FIG. 11 has fewer grains than the examples of FIGS. 8-10, but the ignition configuration and timing produce a relatively more complex pressure versus time profile. The fore end surfaces of both pairs of grains are ignited, in sequence, but only the aft end surfaces of the second pair of grain segments are ignited simultaneous with ignition of the fore end surfaces of the second pair grains. Consequently, the second grains burn faster, producing more gas in a shorter amount of time than the first pair. Additionally, the timing of the ignition of the second pair of grains is set to occur in such a way that gas production from the first grain pair ends about halfway through the burn phase of the second pair. Therefore, the pressure versus time profile 256 drops after the first pair of grains is completely consumed.

The grain and ignition configurations 260, 262, 264 and 266 of the example of FIG. 12 are depicted in FIGS. 12A, 12C, 12D and 12F. As with the examples of FIGS. 7 and 11, the gas producing assembly has only two grain pairs, but the grain pairs are different in size, and the ignition configuration of the two grain pairs are different. Only the fore end surfaces of the first grain pair are ignited. The first grain pair provides a pressure versus time profile 268 having a relatively low-level pressure sustained for a relatively long period of time. In contrast, the second pair of grain segments, while smaller, produce a much higher gas pressure, though over a relatively short period of time, through the ignition of the grains in the second pair at three different locations. The grain segments in the second pair are ignited at the fore end surfaces, the aft end surfaces and at interior locations in the second grain pair, as indicated by the designation "2c" in FIGS. 12D and F. Consequently, the grain segments in the second pair burn from three different locations, namely from the two opposite end surfaces, and as shown in 270 in FIG. 12B, from an approximate middle portion of the two grain segments. The igniter leads can produce ignition if they are located interior to the grains, or adjacent the tube 166. It is preferable that burning of the grains does not occur from the outside in, so igniting the grains near the outer walls is not as desirable. Because the grain segments are supported at the outer walls, burning of the grain segments at the outer walls first is not desirable.

The pressure versus time profile shows a sustained level and a relatively high pressure peak due to the simultaneous ignition of three surfaces or three locations on the grain segments of the second pair. The first pair of grains burn relatively slowly while the second pair of grains burn relatively quickly.

Having thus described several exemplary implementations of the invention, it will be apparent that various alterations and modifications can be made without departing from the inventions or the concepts discussed herein. Such operations and modifications, though not expressly described above, are nonetheless intended and implied to be within the spirit and scope of the inventions. Accordingly, the foregoing description is intended to be illustrative only.